

The Digital Motion Control System for the Submillimeter Array Antennas

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ABSTRACT

We describe the design and performance of the digital servo and motion control system for the 6-meter diameter parabolic antennas of the Submillimeter Array (SMA) on Mauna Kea, Hawaii. The system is divided into three nested layers operating at a different, appropriate bandwidth. (1) A rack-mounted, real-time Unix system runs the position loop which reads the high resolution azimuth and elevation encoders and sends velocity and acceleration commands at 100 Hz to a custom-designed servo control board (SCB). (2) The microcontroller-based SCB reads the motor axis tachometers and implements the velocity loop by sending torque commands to the motor amplifiers at 558 Hz. (3) The motor amplifiers implement the torque loop by monitoring and sending current to the three-phase brushless drive motors at 20 kHz. The velocity loop uses a traditional proportional-integral-derivative (PID) control algorithm, while the position loop uses only a proportional term and implements a command shaper based on the Gauss error function. Calibration factors and software filters are applied to the tachometer feedback prior to the application of the servo gains in the torque computations. All of these parameters are remotely adjustable in software. The three layers of the control system monitor each other and are capable of shutting down the system safely if a failure or anomaly occurs. The Unix system continuously relays the antenna status to the central observatory computer via reflective memory. In each antenna, a Palm Vx hand controller displays complete system status and allows full local control of the drives in an intuitive touchscreen user interface. The hand controller can also be connected outside the cabin, providing a major convenience during the frequent reconfigurations of the interferometer. Excellent tracking performance ($\sim 0.3''$ rms) is achieved with this system. It has been in reliable operation on 8 antennas for over 10 years and has required minimal maintenance.

Subject headings: Telescopes – Instrumentation: miscellaneous – Instrumentation: interferometers

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1. Introduction

The successful operation of tracking interferometers for astronomy demands a safe, reliable, and accurate servo system to control the motion of the primary reflector and the supporting mount of each telescope. For radio interferometers, the pointing and tracking requirements of the individual telescopes depend upon the reflector diameter and the observing frequency. The operational safety requirements include the protection of the mechanical structure of the telescope and the protection of observatory staff and visitors to the site. Safety is an essential concern for facilities that support remote observing, particularly in areas where public access is allowed.

The Submillimeter Array (SMA)¹ consists of eight 6 m diameter antennas arranged among 24 concrete pads near the summit of Mauna Kea, Hawaii (Blundell 2007; Ho et al. 2004; Moran 1998). The various specifications for the SMA place stringent requirements on the antenna servo for tracking accuracy, slew rate, and settling time. For interferometers, tracking errors result in two deleterious effects: (1) loss of signal from sources at the phase center due to the finite extent of the single-dish primary beam response, and (2) improper weighting of radiation over the synthesis area leading to loss of image fidelity, especially for mosaicked observations of extended objects (Bhatnagar et al. 2008). The specified frequency range of the receivers covers 180-900 GHz (Blundell 2005; Hunter et al. 2005), resulting in a primary half-power beam width that ranges from $\theta_{\text{beam}} = 66$ to 13 arcseconds. A desirable goal for pointing accuracy is to maintain $\Delta\theta < (\theta_{\text{beam}}/20)$, which will hold the total power fluctuations below 0.5% for a source at the center of the primary beam (Napier 1989). For the SMA to meet this criterion at the highest operating frequency, the pointing and tracking errors must be kept below $0.7''$.

The ability to perform “fast switching” between the target source and a gain calibrator is also desirable for optimal gain calibration of the interferometer (Holdaway et al. 1995), particularly when observing in the highest frequency bands (Hunter et al. 2007). In practical terms, the number of quasars brighter than 1 Jy at 230 GHz and accessible to the SMA is usually about 50 and they are coarsely distributed over the observable sky of ~ 36000 square degrees (SMA 2012; CARMA 2012). Thus, the typical angle between a target source and the nearest calibrator is $\sim 15^\circ$, although the recent improvements to the SMA bandwidth and receiver performance (Tong et al. 2012) will tend to push this value lower as fainter calibrators can be used. In any case, the power spectrum of atmospheric path length variations versus time typically rises with an exponent of 0.7 (Masson 1994; Kimberk et al. 2012), starting from the shortest time scale – the antenna diameter divided by the wind speed (about 1 second for the SMA on Mauna Kea) – up to a characteristic timescale (100-200 sec for Mauna Kea) beyond which the spectrum of the variations flatten. This timescale is often called the “corner time” and corresponds roughly to the time required for the turbulent phase screen to cross the interferometer. If left uncorrected, these variations will cause decorrelation of

¹The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory (SAO) and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) and is funded by the Smithsonian Institution and the Academia Sinica.

the astronomical measurement. This atmospheric decorrelation can be reduced if the calibrator and target source are close together on the sky and are observed periodically with a cadence less than the corner time. Thus, slew speeds of a few degrees per second and rapid settling times (of 1-2 seconds) are necessary to maintain a high duty cycle in observing the target source.

There are remarkably few papers in the astronomical literature that describe the design of high performance telescope servo systems and encompass all the practical aspects involved from high-level software to low-level hardware. One of the most complete examples is the description of the digital servo developed for the Onsala 20 m telescope (Olberg et al. 1995). The goal of this current paper is to present the detailed design and performance of a modern digital servo and motion control system that has been implemented on the SMA antennas, including a description of the extensive safety features and the novel portable controller. Not included is any discussion of the control system of the subreflector mirror which is based on a commercially available controller (Cheimets 1994), nor is the calibration of the telescope pointing models treated, as it is described in Patel & Sridharan (2004). Although the mechanical components of the SMA antennas were constructed by subcontractors, the SMA partners (SAO and ASIAA) assembled the antennas which provided an opportunity for the in-house development of a precise servo system to meet the scientific needs of the telescope. The scientific and technical staff of the SAO submillimeter receiver lab designed, fabricated, and tested the servo in 1998-1999. It was first commissioned and tested on an SMA antenna at the temporary SAO site at Haystack Observatory in late 1999 and early 2000. Many improvements and conveniences to the software were added over the subsequent two years based on experience from operations at the Mauna Kea site. The paper begins by describing the fundamentals of antenna servo control in §2, including some relevant information on the SMA antenna structure and its open loop response. The hardware and software design of the servo system is presented in §3 and the Palm Vx portable controller is described in §4. The key performance measurements are given in §5.

2. Antenna servo fundamentals

2.1. Basic equations

The fundamentals of servo systems for accurate dish antenna positioning were first presented by Lozier et al. (1963) for hydraulic drives. Regardless of the type of drive, motors are typically connected to antennas through gearing, which effectively reduces the moment of inertia of the antenna (J_a) as seen at the motor shaft. The equivalent or “reflected” inertia (J_{eq}) is given by:

$$J_{eq} = R^2 J_a = \left(\frac{N_1}{N_2} \right)^2 J_a \quad (1)$$

where R is the gear ratio, for example in a two-gear system of N_1 and N_2 teeth (Klafter et al.

1989). Alternatively, a similar reduction in antenna inertia can be achieved with a leadscrew or ball screw drive, which converts rotary motion of a shaft into linear motion of a mass (M) through its coupling ratio or pitch (P) in units of turns per distance traveled. In this case, the equivalent inertia is given by:

$$J_{\text{eq}} = \frac{M}{(2\pi P)^2}. \quad (2)$$

Because only a limited range of motion ($< 90^\circ$) is typically required, leadscrews are sometimes employed to drive antennas in elevation, for example the Leighton antennas of the Caltech Submillimeter Observatory (Woody et al. 1994) and the Combined Array for Millimeter Astronomy (Woody et al. 2004).

The moments of inertia of the antenna (J_a) and the motor (J_m) for one axis of motion, combined with the maximum desired values for the angular velocity ($\dot{\theta}_a$) and angular acceleration of the antenna ($\ddot{\theta}_a$) for that axis, will determine the levels of motor torque (T_m) that must be generated to meet the system goals. The fundamental relation between these quantities and the motor torque constant (κ_T), the applied armature current (I), the Coulomb and viscous bearing friction coefficients (C and B), which may both be a function of their respective axis angle (θ), and the spring constant of the system (k) is given by the second order differential equation for a moment of inertia-damper-spring system running open-loop² (see e.g. Van de Vegte 1993):

$$T_m = \kappa_T I = \underbrace{(J_m + R^2 J_a)}_{\text{inertia}} \ddot{\theta}_m + \underbrace{(B_{m,\theta_m} + R^2 B_{a,\theta_a})}_{\text{viscous friction}} \dot{\theta}_m + \underbrace{(C_{m,\theta_m} + R C_{a,\theta_a})}_{\text{Coulomb friction}} + \underbrace{k(\theta_m - R\theta_a)}_{\text{spring}} + R T_{\text{wind}} \quad (3)$$

The torque applied by the wind to an antenna axis (T_{wind}) is a complicated function proportional to the air density, the wind velocity squared, and an integral over the area of the antenna structure projected toward the wind times an effective radius from the axis and a drag coefficient (see e.g. Levy 1996; Campbell 2004). The torque delivered to the antenna axis (T_a) can be written as a sum of the antenna frictional terms and the remaining torque available to accelerate the antenna load ($J_a \ddot{\theta}_a$):

$$T_a \equiv C_{a,\theta_a} + T_{\text{wind}} + B_{a,\theta_a} \dot{\theta}_a + J_a \ddot{\theta}_a = T_m - \frac{J_m}{R^2} - \frac{B_{m,\theta_m} \dot{\theta}_a}{R^2} - \frac{C_{m,\theta_m}}{R} - k \left(\frac{\theta_m}{R} - \theta_a \right) \quad (4)$$

The torque required to maintain even a constant angular velocity will vary with time and angular position of the telescope due to any number of minor disturbances including variable

²Not represented in the Coulomb friction term in equation 3 is the property of static friction (stiction) which is an increase in friction at zero velocity.

friction in the gear dynamics and bearings, and wind forces. Thus, the goal of a servo system is to continuously observe the dynamic state of the antenna by reading feedback instruments, computing the following error with respect to the desired or expected trajectory, and adjusting the applied torque in order to minimize this error. Typically, the resonant frequencies of the mechanical structure impose a practical limit on the maximum value of $\ddot{\theta}$ that one can apply. In other words, to avoid exciting the structure, the servo bandwidth must be limited to less than the lowest resonant frequency, or employ notch filters to mask the response. Antenna servo design draws upon the general techniques of feedback control systems which are described in various engineering textbooks (see e.g. Franklin et al. 2005). While there has been recent research on alternative servo algorithms for large radio telescopes (Smith & Souccar 2010; Zhu et al. 2007; Gawronski & Souccar 2005), the conventional proportional-integral-derivative (PID) control algorithm has been the most traditional approach. Fundamentally, a PID-based controller periodically computes the difference between the measured position and velocity and their corresponding target values. The P term is based on the present error, the I term is based on the accumulation of errors in the (recent) past, and the D term is based on how rapidly the error is currently changing. These three terms are typically combined into a weighted sum using individual gain factors before being applied to the motor amplifier as the new desired torque value.

2.2. SMA antenna properties

The SMA antennas (Figure 1) consist of a 6 m diameter parabolic reflector comprised of aluminum panels attached to a backup structure of carbon fiber tubes and steel nodes sitting atop a stiff steel mount which houses the receiver system in a temperature controlled environment. The antennas are driven along azimuth and elevation axes using brushless three-phase motors with a peak torque of 1085 N m, similar to those used by the Cosmic Background Imager (Padin et al. 2002). In azimuth, there are two motors meshed to a 2.14 m-diameter bull gear at a tooth ratio of 422:30 (14.0667:1). The bull gear remains stationary with respect to the pad as the rotating portion of the antenna mount drives around it. In elevation, a single motor drives a ballscrew whose effective gear ratio varies with elevation from ~ 315 at 45° dropping to ~ 250 at 15° and 87° (Fig 2). The ballscrew nut moves away from the motor as the telescope moves upward in elevation. The total range of motion between the hardstops is -178° to $+357^\circ$ in azimuth and 6.7° to 89° in elevation. The relatively small gear ratio in azimuth means that the reflected moment of inertia (including counterweights) is dominated by the antenna structure (61450 N m at zenith, 311 N m reflected), whereas in elevation the inertia contributed by the motor and the directly-driven lead screw (1.39 N m) is of similar magnitude to that of the antenna (58270 N m, 0.95 N m reflected). Thus, it is clear that azimuth will be the more challenging axis to control smoothly as the antenna dynamics will be more influential.



Fig. 1.— Photograph of an SMA antenna on Mauna Kea. The azimuth counterweights are located at the bottom front of the mount and the elevation counterweights are the inverted T-shaped pieces behind the dish. The elevation ballscrew protrudes from the cabin and is covered by the black cylindrical bellows.

2.3. Open loop response

When designing a servo, it is crucial to first understand the frequency response of the system to the applied torque. Finite element models (FEM) of the SMA antenna indicate that the lowest natural frequency of the telescope assembly is a bending mode of the mount at 14 Hz (Raffin 1991). Additional bending and torsional modes of the reflector, backup structure, and quadrupods occur at frequencies above 16 Hz. These predictions were tested after construction of the prototype antennas at Haystack Observatory in the following manner. One azimuth drive motor was excited with sinusoids at a sequence of frequencies and the response of the high resolution encoder was recorded in order to generate a Bode plot of the open loop response. Significant resonances at 13 and 19 Hz were found, which differ somewhat from the FEM result, along with an additional weaker feature near 8 Hz. In a similar experiment, one azimuth motor was excited with sinusoids while the

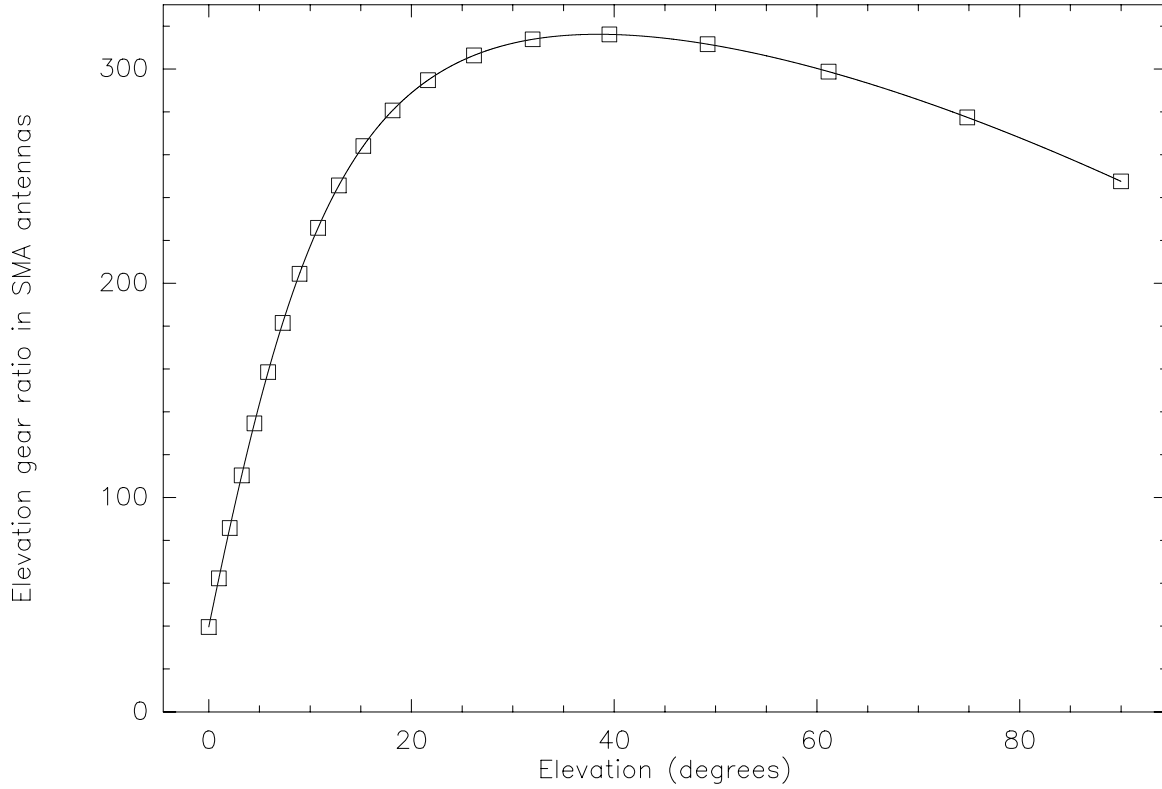


Fig. 2.— The gear ratio of the SMA elevation ballscrew drive as a function of antenna elevation, given in degrees above the horizon.

response of the tachometer on the other azimuth motor was recorded. A resonance in the elevation counterweights was found which explained the lowest frequency feature. This is not surprising since the FEM was made for the original design of the SMA antenna which was unbalanced in both axes and planned to use "electronic counterweights" instead of physical counterweights. Clearly these resonances will need to be avoided by the servo controller.

3. Servo System Design

3.1. Conceptual design

Initial attempts to drive the prototype SMA antennas using a commercial servo controller yielded less than optimal results and had a rather arcane command interface. It also suffered from considerable stiction in the elevation drive screw at low elevation angles because of the lack of counterweights and poor mechanical advantage at low elevation angles. As a result, it was

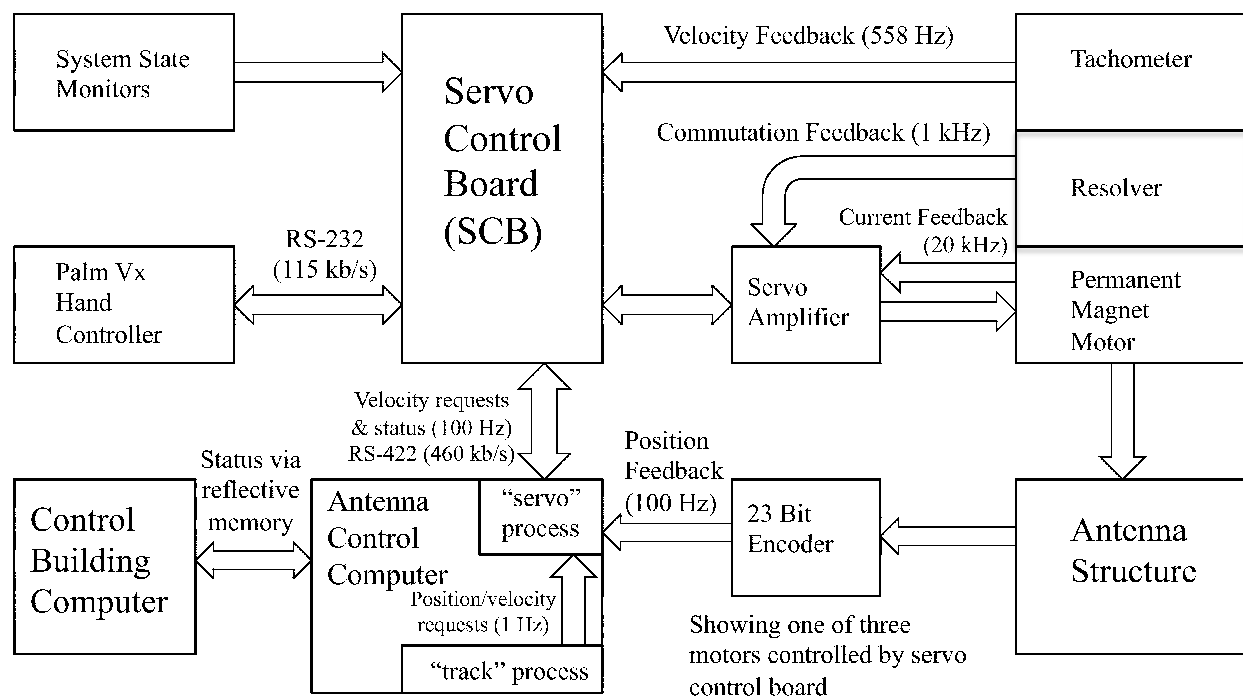


Fig. 3.— Diagram of the servo control system for the SMA antennas. The feedback occurs at the following rates: position: 100 Hz, velocity: 558 Hz, motor commutation: 1 kHz, and motor current: 20 kHz.

decided to add physical counterweights and to create a reliable digital servo control system designed around a well-established microcontroller placed on a custom integrated circuit board comprised of standard components and interfaces, and programmed in the widely-adopted C programming language. This design led to an effective division of the PID control concept into three nested layers, each implemented in a different processor, and each running an independent PID servo loop. While it may seem complicated, the design leads to a natural division of labor between the motor amplifier circuitry, a rugged embedded system, and a networked Unix computer.

A basic diagram of the design is shown in Figure 3. Forming the bottom layer, the motor amplifiers execute the highest bandwidth (~ 20 kHz) servo loop by monitoring and controlling the current delivered to the motors. The middle layer is implemented by a custom-designed servo control board (SCB) containing a microcontroller which closes the velocity servo loop around the motors by reading the tachometers, calculating new torque commands and sending them as voltages to the motor amplifiers at 558 Hz. This loop is a full PID loop with relatively high integral gain so it behaves somewhat like a position control on the motor shaft. (The derivative term is zero in azimuth and not very important in elevation.) In the case of torque overload (that is, when the computed torque request would exceed the maximum output value), the integral term is constrained to a smaller (or zero) value in order to constrain the delivered request to be within the controlled

range.

The highest servo layer executes on each antenna control computer (ACC), a diskless, network-booted, VMEbus Power PC running a flavor of real-time Unix (LynxOS). A server process on this machine administers the position servo loop by receiving position and velocity requests once per second, reading the position encoders, and computing and sending velocity commands to the SCB at 100 Hz. This top level loop is a simple position loop with relatively low gain to avoid exciting structural resonances. It compensates for the low gain by having accurate velocity feed forward to the relatively stiff motor velocity loop. The 100 Hz timing is maintained via programmed interrupts received from a synchronized generator card on the VMEbus.

Among the three layers, there is redundant monitoring of control parameters, as the three layers monitor each other and are capable of shutting down the system if any measured quantities become out of the nominal range. Conceptually, the three layers also divide the task of programming in a natural progression, with the Power PC being the easiest to program as it requires no knowledge of the underlying hardware, while at the other end, the optimization of the motor amplifier circuitry requires advanced electrical engineering skills. Although this digital control system could easily be used to implement and test alternative control algorithms, such as linear-quadratic-Gaussian (LQG) and H-infinity (Gawronski 2001), the performance of this more traditional PID system meets the required specifications, after a couple of digital tweaks such as resetting the integrator upon overload and using an optimal strategy for torque bias (§3.3.1).

3.2. Hardware components

3.2.1. Motors and motor amplifiers

Each motor is a 32 pole brushless, permanent magnet rotor, torquer. The stator electromagnets are driven by three-phase power emitted by a pulse width modulated (PWM) current controller (7 Amp Volt⁻¹) operated at ~ 20 kHz and located on the motor amplifier circuit boards (manufactured by Glentek). Motor current feedback is supplied by Hall effect transducers. The torque constant of the motors is $\kappa_T = 16.3$ N m Amp⁻¹ with a maximum acceleration of 3070 rad s⁻². Considering the gear ratios, the motor-amplifier system produces 0.041 rad s⁻² Amp⁻¹ at the azimuth motor and 23.6 rad s⁻² Amp⁻¹ at the elevation motor. In terms of dish motion, these values equate to 0.17° s⁻² Amp⁻¹ in azimuth and 4.5° s⁻² Amp⁻¹ in elevation.

A small resolver is attached to the shaft of each motor and is excited at 1 kHz. Its feedback is used in apportioning the drive current to the three motor windings so that the resulting magnetic field exerts the desired torque on the permanent magnet rotor. The motors can be commutated at any one of the six possible motor phase combinations. Due to the low inductance of the torquer (6 mH), series inductors were added to each of the three power wires in order to increase the time constant for the current rise and thereby reduce the level of electrical noise emitted into the

electronic environment of the antenna. As a safety feature, the maximum velocities were set in hardware to approximately 6° s^{-1} (azimuth) and 3° s^{-1} (elevation) by choosing the appropriate resistors and capacitors for the components associated with the AD2S83 resolver-to-digital converter integrated circuit. This device demodulates the resolver sine/cosine output and provides a 16 bit output for the commutation circuit. The azimuth value was chosen to prevent the dish from breaking loose from the mount during a rapid deceleration from this velocity when encountering the hardstop, and the elevation value was chosen so that the stopping impact would not exceed the maximum dissipation of the rubber hardstops. The servo system in turn limits the maximum controlled slew velocities to 4° s^{-1} and 2° s^{-1} , respectively. The amplifiers have a dynamic brake feature which is disabled during normal operation but will engage in a commanded or emergency shutdown.

3.2.2. *Microcontroller*

The SCB is built on a 24×24 cm four-layer printed circuit board (see Figure 4). The processor at the heart of the SCB is an Intel 80C196KC 16-bit microcontroller running at 20 MHz on an 8-bit bus. This is the same controller used to operate the digital phase lock loop and Gunn oscillator and attenuator motors on the front-end first local oscillators (Hunter et al. 2011, 2002). A C language cross-compiler (Tasking, Inc.) is used to generate the executable code. The microcontroller manages a multitude of hardware devices:

- 40 digital inputs: to read limit switches and fault indicators
- 32 digital outputs: to enable, disable, or reset the motor amplifiers, apply or release the mechanical or dynamic brakes, and to drive the environmental door that protects the receiver cabin from the weather
- a four channel 22-bit ± 2.5 V analog to digital converter (ADC): to read the motor tachometers
- a four channel 16-bit ± 5 V digital to analog converter (DAC): to provide torque commands to the motor amplifiers via balanced differential drivers
- an RS-422 serial port: to communicate with the ACC (460 kbps)
- an RS-232 serial port: to communicate with the Palm Vx hand controller (115 kbps)
- synchronous serial ports: to read the low-resolution "coarse" encoders on the azimuth and elevation axes.
- a 32-LED indicator panel with serial interface: to display system status to personnel working in the antenna cabin

Each section of the board employs independent ground planes and power supplies, with optical isolation on all I/O channels. There are convenient test points installed to allow easy debugging of the analog signals either arriving at, or generated by, the SCB. The microcontroller program runs from an erasable programmable read only memory (EPROM). During the development phase of the SCB, over a dozen different simple programs were devised and written to individual EPROMs to test specific hardware devices on the board and which displayed the test results on the LED status panel. For the third (and final) revision of the circuit board, twenty boards were constructed.

3.2.3. Feedback devices

Antenna velocity

Motor velocity feedback is provided by brushed tachometers that are installed on each motor axis and have a gain of $12 \text{ V}/(\text{rad s}^{-1})$, which equates to $2.95 \text{ V}/(\text{deg s}^{-1})$ in azimuth and $63 \text{ V}/(\text{deg s}^{-1})$ in elevation. The tachometer signals are divided by resistor networks on the SCB ($\div 4.734$ in azimuth and $\div 53.22$ in elevation) and sampled by a 4-channel Sigma-Delta 22-bit ADC. Following digitization, the SCB applies the empirically derived tachometer calibration factors that are stored in memory so that the velocity feed-forward will be accurately applied. Whenever the servo is disabled, the ADC readings are still continuously collected and used to automatically define the zero offset value. The 10-bit ADC onboard the microcontroller is used to monitor the temperature and current of the three motors via an eight-input multiplexer.

Antenna position

Antenna axis position feedback is provided by two sets of encoders: “coarse” encoders that provide absolute antenna position to the SCB and “fine” encoders which provide high resolution absolute position to the ACC. The coarse encoders (manufactured by Stegmann) are 24-bit devices with 4096 counts per turn and 4096 turns connected to the SCB via a synchronous serial interface. They are connected to the antenna axes by gears and have a resolution of about 0.0052° in azimuth and 0.023° in elevation at the antenna axes. The calibrated offset values corresponding to zero azimuth and zero elevation are stored on the SCB in non-volatile static random access memory (NVS RAM) backed up by an electrically erasable read only memory (EEPROM). These encoders are used by the SCB to enforce “soft” limits in order to avoid engaging the hardware limit switches during normal operations, which would shut down the system and require operator intervention. The nominal values of the soft limits are -171° to $+349^\circ$ in azimuth and 14° to 87.5° in elevation. The SCB also repeatedly sums the tachometer signals for 100 servo cycles and compares the result to the change in the corresponding coarse encoder as a safety check that both devices are working properly.

A high resolution encoder (manufactured by Heidenhain) is directly driven by each axis. They

are read using Heidenhain’s EnDatTM protocol by the position loop on the ACC, which stores the corresponding zero values in a configuration file. The original encoders had 23 bits (for a resolution of 0.154”) but a few antennas have a newer model of the same geometry with 27 bits.

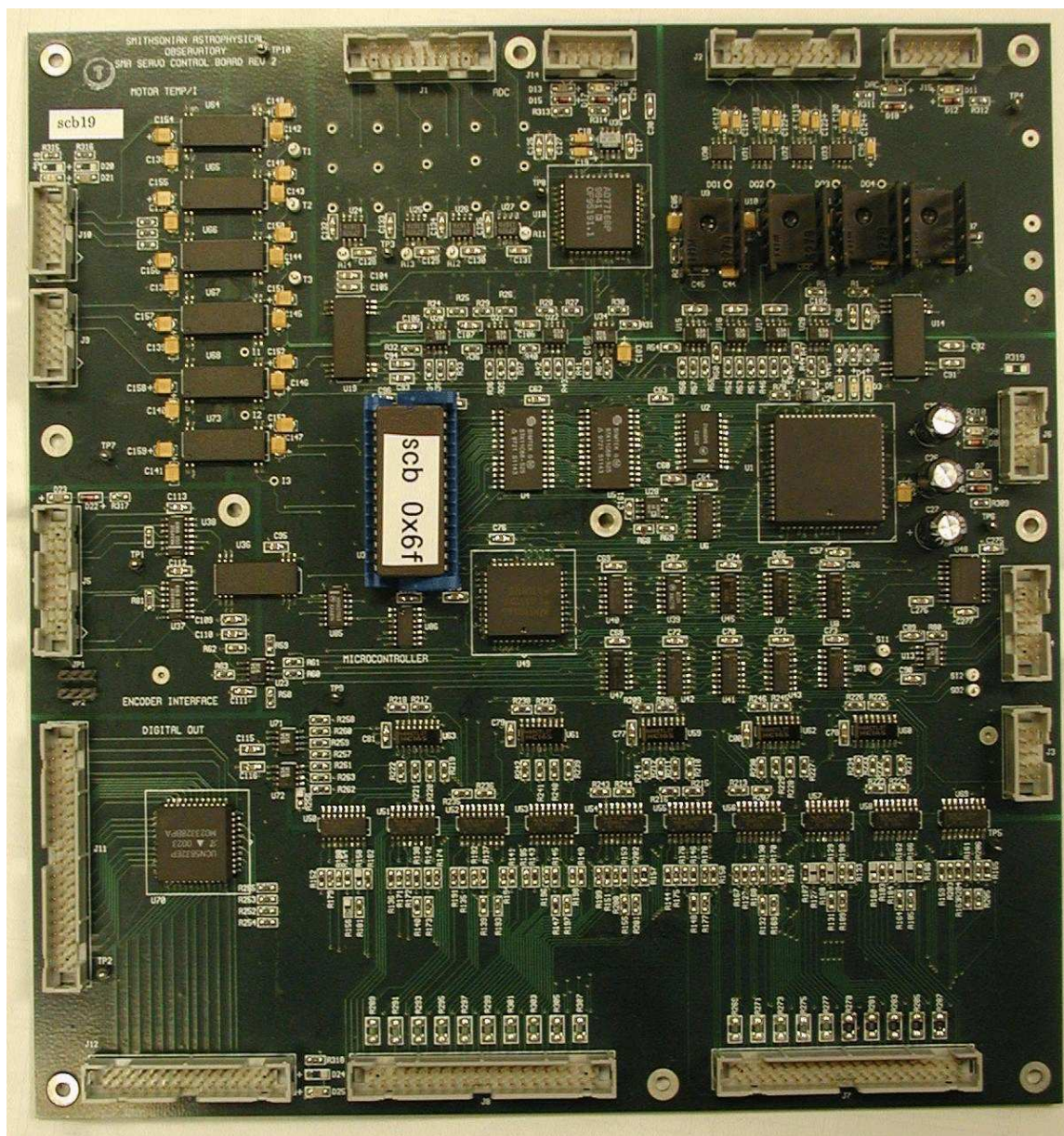


Fig. 4.— Photograph of the 24 cm servo control board (SCB) which is installed in each SMA antenna. The Intel microcontroller is the large integrated circuit located to the right of the center, and the EPROM containing the control code is the chip to the left of center with the version label attached and installed in a zero-insertion force socket.

Motor faults and limit switches

A large number of digital inputs bring system information to the SCB. Each of the three motor amplifiers produce a fault signal which is monitored by the SCB. Two pairs of limit switches are installed near the end of travel of each axis: a “pre-limit” which triggers a software servo shutdown, and a “final” limit which disengages the power relay to the motor amplifiers for that axis. The open collector arrangement guarantees that a broken wire always causes the limit switch to appear as if it was engaged. The SCB can be commanded to temporarily override the soft limits and/or the pre-limits (for a fixed time interval) to allow manual escape of a pre-limit via the Palm Vx hand controller. In order to escape an engaged final limit switch, there is a momentary button switch in the cabin which will allow the power relay to be energized while the button is depressed. In addition, there is a limit switch that monitors the orientation of the azimuth rocker arm, which deploys the azimuth hardstop in one of two positions depending on which azimuth wrap the antenna is currently operating (the normal azimuth range is -176° to $+353^\circ$). Finally, there are two limit switches that indicate the position of the environmental door (fully closed or fully open) which is located just above the antenna elevation axis and can be commanded to seal the cabin from the outdoor weather. In this case, it blocks the optical path from the subreflector to mirror #3, a flat mirror which rotates on the elevation axis and illuminates the fixed receiver optics (Paine et al. 1994). Hence, it is often called the “M3 door”.

Pad identification

Five digital inputs are used to sense the identification code for the antenna pad (the pad ID). This code is established by resistors in a cable terminator attached to each pad, and is relayed back from the SCB to the ACC and the SMA control system. The SCB uses this code to recognize when it is on the transporter and adjusts the servo gains to the appropriate preset values automatically. It also uses this code to recognize when it is occupying a position on the inner ring of eight pads where a collision between antennas can be possible if the array is in the “subcompact” configuration. In this case, the SCB will read an additional limit switch which effectively increases the low elevation software limit to 32° . For additional safety, a physical wedge is also installed on the antennas in this configuration to raise the elevation hard stop to $\sim 30^\circ$, which is sufficient to preclude any collision. There is a mechanism in software to use a fake pad ID if the readback code corresponds to an invalid pad number. Following the commissioning phase of the SMA, this feature has been used only rarely (and temporarily) in the case that the cable terminator is damaged or left unconnected after a reconfiguration.

Emergency stops

An emergency stop (E-stop) circuit is implemented in each antenna which cuts power to the motor amplifiers. It is comprised of a sequence of buttons both inside and outside the antenna cabin, on

the Palm Vx hand controller, and in the central control building via a fiber optic link. In addition, the ACC can engage the E-stop via a digital output bit that controls a switch in the circuit. One digital input on the SCB monitors the E-stop circuit status.

Coolant flow and brakes

Because all three motors are liquid cooled, there is a coolant flow sensor located along the coolant flow tube which indicates whether there is sufficient flow present and it is monitored by the SCB. The azimuth brakes are released by air pressure, and the pressure in the air ballast tank is monitored by a gauge which produces a low pressure signal connected to the SCB. The release status of the elevation brake is also monitored.

Status display panels

Continuous feedback to personnel in the antenna cabin is provided by the SCB via a 15 cm panel of 32 color-coded LED indicators which indicate the status of the servo and all the associated limit switches and possible error conditions. In normal active operation, all indicators illuminated are green, while error conditions are shown by red indicators. In a similar manner, the commercial motor amplifier cards have 13 color-coded indicators that indicate either normal operation or which reason(s) has triggered the fault.

3.3. Software components

3.3.1. SCB microcontroller software

The 80C196KC microcontroller executes an interrupt-driven, scheduler-based program written in C and assembled into the 64 kB EPROM with the program variables (and some functions) stored in two banks of 8 kB of NVSRAM/EEPROM.

Scheduler

The main loop of the EPROM program is a subroutine scheduler. Whenever the program is not servicing an interrupt, the scheduler continuously works its way down through a possible list of 11 jobs in order of descending priority. The list of jobs along with a brief summary is given below:

1. FASTSERIAL: read the encoders and digital inputs; schedule the SAFETY and WATCHDOG jobs
2. SYSTEM: sequence the startup/shutdown (motor amplifier power and coolant pump)

3. AZ.SEQUENCE: enable/disable the azimuth servo and/or braking
4. EL.SEQUENCE: enable/disable the elevation servo and/or braking
5. ACC.REQUEST: process the serial packet commands from the ACC
6. SAFETY: check the digital inputs, encoder range, and ADC status; schedule the SYSTEM, AZ.SEQUENCE, or EL.SEQUENCE jobs as needed
7. SLOWSERIAL: update the digital outputs and the LED status board
8. M3: operate the “mirror #3” environmental cabin door
9. HORN: sound the external horn prior to a significant slew
10. PALMPADDLE: send the servo status variables to (and/or process commands from the Palm Vx)
11. WATCHDOG: clear the timer if all is well and ACC packets are being received

Each job has an indicator as to whether it has been scheduled and needs to be executed. For example, when the FASTSERIAL job completes, the program checks if the SYSTEM job has been scheduled. If so, it executes that job, otherwise it next checks AZ.SEQUENCE, and so on. The activity of the scheduler is paced by two interrupt service routines that run periodically and always take precedence over the 11 jobs above: the ADC “data ready” interrupt and the “incoming serial data” interrupt. The “data ready” pin of the 22-bit ADC periodically drives the main interrupt of the microcontroller at a rate of 558 Hz, triggering the ADC interrupt service routine which reads the ADC, computes new torque commands, and schedules calls to SLOWSERIAL and FASTSERIAL. Similarly, the arrival of an RS-422 serial packet at the universal asynchronous receiver/transmitter (UART) chip on the SCB triggers the serial interrupt service routine which decodes the packet and schedules ACC.REQUEST. Under normal operation, the velocity requests arrive as serial packets at 100 Hz from the command-shaping, position loop servo process running independently on the ACC. Each packet contains: (1) a start byte beginning with 0xc0 and encoded with the packet type (of which there are 64), (2) the content bytes, (3) a two byte value resulting from a cyclic redundancy check calculated over the content bytes, and (4) a new line character as the stop byte. The content bytes (up to 32) are encoded such that their sign bits are stripped and assembled into an additional byte included after every sixth content byte. The SAFETY job, which performs a variety of telescope safety checks such as reading limit switches, gets scheduled (by the FASTSERIAL job) on every other interrupt cycle (279 Hz) and can trigger shutdowns accordingly. Similarly scheduled, the WATCHDOG job performs the routine servicing of a 6 millisecond watchdog timer; thus if the microcontroller CPU is ever overcome by the jobs to be run, it will be reset very quickly, and its default outputs upon restart will trigger an immediate shutdown of the servo.

The microcontroller provides register space for the storage of important variables. This space is used to record the amount of spare time remaining upon completion of all the tasks in each

interrupt service execution. It also contains two 32-bit fault words: the current list of faults and the list of faults present upon the last execution of the non-maskable interrupt handler, which will run only in the event that the microcontroller is reset or powered off. The stored faults will then only be cleared after they are read by the ACC. Because the register variables are unspecified at power up, a mirror copy of each is kept in SRAM and copied to the registers at system startup. This includes a copy of the low resolution encoder positions, which is useful in the event that an encoder needs to be temporarily removed, as the final received antenna position will be retained and continue to be displayed to the rest of the upstream system after a power cycle, up until the encoder is able to be reconnected.

Velocity servo loop parameters

The velocity servo loops receive updated velocity and acceleration commands at 100 Hz from the "servo" process on the ACC. The acceleration value is used to smoothly interpolate the velocity commands between updates to reduce noise and, probably, mechanical wear. Two digital software lag filters centered at 12 Hz and 18 Hz are applied to the azimuth tachometer feedback signal to prevent amplification of azimuth resonances. The gains and filter parameters are set in software and can be remotely modified. This capability is most critical during the commissioning and servo tuning phase as it is not possible to pre-determine optimal values for all the servo parameters (Gawronski 2007). The optimal gains will provide a critically damped step response which does not contain spectral components that excite the structure. In order to arrive at the optimal gains, the gains were adjusted manually to obtain fast acquisition after a slew, and smooth tracking at various speeds. The general approach was to start with low gain and increase it until overshoot or oscillatory behavior started, increasing the damping as helpful, but eventually backing off to achieve the fastest settling time to within an arcsecond of the new trajectory after a slew, over a variety of cases. The tools described in §3.3.2 were used to drive the system and collect performance data during this process.

The ability to modify the gains in software is also important for long term operations of antennas that are part of reconfigurable interferometers like the SMA, as the servo gains will be quite different when the antenna is carried by a transporter (during which time small motions may be necessary in maneuvering) compared to when it is fastened to a very stiff concrete pad.

Azimuth torque bias

One of the two azimuth motors is primarily used to drive the antenna clockwise, while the other motor is used to drive it anti-clockwise. To provide a torque bias, the alternate motor is driven with 10% of the torque in the opposite direction. This bias minimizes backlash and gear wear as the motor velocities vary to compensate for small disturbances during slewing and tracking. In the case that the primary motor reaches its torque limit, the second motor is commanded to reverse and join the primary motor. The maximum acceleration has been set such that this only happens

very rarely, such as during a particularly strong wind gust. The servo software also supports the option of single azimuth motor operation, in which case that motor receives the torque command directly and there is no torque bias.

3.3.2. ACC software

For remote operation of the antenna, two processes on the ACC are started. The first process (called “track”) handles the ephemeris information and computes new positions and tracking velocities in altitude and azimuth coordinates once per second. Details on the calculations as a function of universal time and celestial coordinates are described in Patel (2000). These positions and velocities are transferred via a segment of shared memory to a second process (called “servo”) which uses these data to compute and send new velocity and acceleration requests to the SCB at a rate of 100 Hz in the form of serial packets. The SCB responds to each of these packets with its status, its torque commands, and the velocities from the tachometers. “Servo” takes care of any error conditions in the SCB or the drive amplifiers, shutting down in response to any dangerous errors. It passes 33 items of status information back to “track” in another part of the same shared memory segment. In a third part of the shared memory segment, “servo” maintains a circular buffer of performance data which is updated at 100 Hz.

To transfer servo information to and from the antennas, there is a fiber-optic based reflective memory system which provides a memory segment shared between the ACC and the central control computer. “Servo” uses this to send messages to the array operator in case of serious problems and to provide 78 status items for monitoring and recording by the central system. These include values which change rapidly like the actual azimuth and elevation down to semi-static items like pad ID and software version numbers. “Servo” updates any status item which has changed every second and the central system records those which have changed once per minute. A high level text-user-interface (TUI) monitor program using the curses programming library for terminal control (Strang 1986) can display most of this information to the operator or any other interested personnel over the internet via a standard terminal application. An example of the antenna drive status display page for one antenna is shown in Figure 5.

For testing, setting servo parameters, and maintenance, two additional computer programs were written. The first – “svdata” – reads the performance data which “servo” places into the servo-track shared memory circular buffer at 100 Hz and writes it to a text file. Plotting this data was extremely useful in initially commissioning the system and has remained useful for maintenance. For example, by recording data during complete upward and downward elevation scans, we are able to measure the balance points of the antennas as the point where the applied torque during the two scans are equal and opposite (mean elevation = 78°). The second – “dmytrack” – interfaces with “servo” in the same way “track” does, but accepts interactive operator commands for azimuth and elevation position and velocity.

Position servo loop parameters

The position servo loop uses a simple proportional control algorithm supplemented by velocity feed forward. The gain is only 5 s^{-1} so the bandwidth is less than 1 Hz. Fast closure after a slew is dependent on accurate velocity feed-forward during the slew so that the final position is near the goal. This in turn depends on accurate calibration of the tachometers in the SCB as discussed in §3.2.3.

3.3.3. Trajectory command shaping

The nested velocity and position loops as described so far work well as long as they stay within their linear range of operation. In order to avoid nonlinearities, it is essential for the position loop running on the ACC to construct and transmit a smooth sequence of values to the velocity loop which are within the ability of the drive system to follow and which do not excite the mechanical resonances of the antenna. An algorithm designed to achieve this result is commonly called a command preprocessor or a trajectory preprocessor (Tyler 1994; Gawronski & Almasy 2002; Smith & Souccar 2008). In this paper, the term command shaper will be used. The three main goals of the command shaper are: (1) to avoid saturating the integrator, (2) to limit the bandwidth required to follow the command so that no component excites a mechanical resonance, and (3) to operate within the maximum capabilities of the system (with a small amount of headroom

Antenna 1 Drive Status: Wed Jan 23 15:09:31 2013 UT, Wed Jan 23 05:09:31 2013 HT							
Track				servo			
state	pos	vel		state	commanded	encoder	limenc Following Error
Az on	223.9561	0.0174		track	223.9657	223.9657	223.929 -0.00001
El on	79.9477	-0.0027		track	79.9462	79.9462	79.990 -0.00004
				Tach Vel: Az 0.0160 El -0.0028 Rocker Neutral			
msecCmd 54570447				msecAccept 54570447 msec 54571000 ttTimeOuts 24			
m3Cmd = 1 = open m3State = 2 = open Collision Check: OFF Sun Az=103 El=-26							
Limits: Az(-171.553, 348.891) El(13.997, 87.461) Rocker(-110.00, +320.00)							
Gains (IPD)				TBias	TDiv	EncT	EncRev
Az (60.0 4.5 0.0)	100.0	948	Heid	No	6.4361	29.3	14.1
El (60.0 2.4 0.4)		951	Heid	Yes	0.0000	25.2	1.6
Lim enc: Az zero				60819, diff	0.0364	El zero	16746438, diff -0.0435
AzAccelMax 4.0 deg/s^2				IRIG-B: Locked (errors=0) TelephoneStow:0 shutdown:0			
EPROM 0x7f SRAM 0xa0 Palm Code Date 24Jan2005				SCB resets 6399 Bad Pkts 0			
Fault word = 0x00000000				SCB Status 0x07 padID = 12, padAzOffset = -0.8369			
Glycol Flow: 2.93				Temp: 15.95 Pressure 67.5			

Fig. 5.— Snapshot of the antenna drive status display page for antenna 1 in the text-user-interface program that monitors the complete SMA observatory status over dozens of pages. Any values in error state will appear in inverse video. The empty bottom line of text is reserved for important transitory messages such as “Emergency stop pressed”.

to allow for minor overshoots). For this command shaper, the Gauss error function (erf) was chosen as originally proposed by Woody (1998). The benefit of a Gaussian shape in the time domain is that it also has a Gaussian shape in the frequency domain; thus, it generates less power at frequencies that could excite the structure compared to a trapezoidal command shape of similar duration.

Similar to the algorithm described in Olberg et al. (1995), the command shaper enters various states depending on the current position and velocity request and the state of motion of the antenna. This is implemented as a state machine which also controls starting and stopping the drive system. During routine observations of sidereal sources, the state machine is typically in the TRACKING state, in which the antenna follows the slow but steady apparent motion of a source across the sky. During the TRACKING state, if the next commanded position ever differs by more than $5''$ from the previous value, or the commanded velocity differs by more than $5'' \text{ s}^{-1}$, then a commanded change of source is inferred and a move sequence is initiated. Given the delivery rate of new positions, this threshold will never be triggered during sidereal tracking unless the elevation exceeds 89° elevation, which is already beyond the elevation software limit.

There are two types of move sequences implemented: “short” and “long”. A short move is one in which the position and velocity are interpolated between their current values and the values they should have at the projected end of the slew with a single error function. (The erf() function has an infinite range, but it is truncated here so that the discontinuity at each end is small but the time spent starting or stopping is minimized.) A long move has three parts: acceleration to the maximum velocity, a (possible) constant velocity part, and a deceleration to the final position and velocity. The acceleration part follows a truncated error function in velocity between the present velocity and the maximum velocity while obeying the maximum acceleration allowed. The deceleration part is similar and timed to join with the requested path in position and velocity. As an example, the response of the system to a short move followed by a long move in each axis is illustrated in Figure 6. When planning a move sequence, the first thing the command shaper does is to plan a short move which stays within the velocity and acceleration limits of the system. If the short move takes less time than a long move would, then it is used. Otherwise a long move is planned and executed.

3.3.4. *Sun avoidance*

The SMA antennas are not designed to directly observe the Sun. The cabling to the subreflector can reach destructive temperatures when the telescope is pointed near the Sun for a significant period of time due to illumination by off-axis caustics. To guard against accidental movements toward the Sun, the server process on the ACC frequently computes the solar position and the number of minutes before it will enter the avoidance zone based on the antenna’s current position. If the number of minutes reaches zero, the Sun has entered the avoidance zone, and the antenna is moved to avoid the Sun. The radius of the avoidance zone (typically 25°) is read periodically from reflective memory so it can be modified by the operator if necessary without restarting the “servo”

process. If a slew command would cross through the sun avoidance zone, but the end point is not within it, then the path is redirected around zone. The avoidance is active even when the telescope is under manual control with the Palm Vx. However, the sun avoidance check is automatically disabled if the pad identification hardware value does not match a normal pad, i.e. it corresponds to the transporter or the indoor pad in the antenna barn.

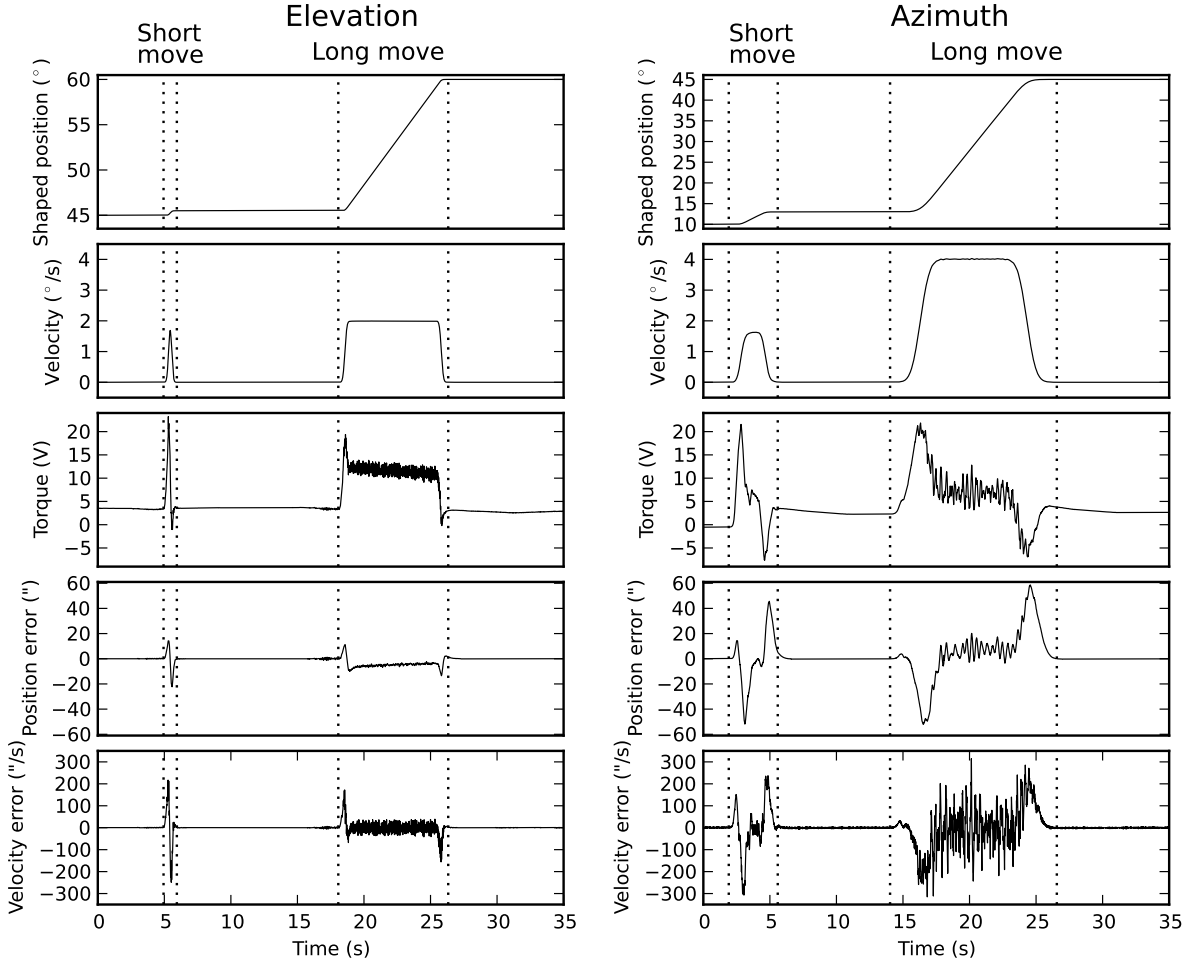


Fig. 6.— The response of the system to a “short” move followed by a “long” move in elevation (left column of plots) and azimuth (right column of plots). Top row: the position command vs. time, as produced by the command shaper. Second row: the velocity command. Third row: the requested torque. Fourth row: the position error (commanded minus actual). Bottom row: the velocity error (commanded minus actual). The vertical dotted lines denote the beginning and end of the movement segment.

3.4. Automatic monitoring features

The three servo loops (position, velocity, and motor current) perform self-consistency checks on the state of the system and can each disable the drive system if these checks fail.

3.4.1. SCB

When the drives are enabled, the following list of conditions (in addition to normal limit switches, azimuth rocker arm deployment check, and E-stops) will cause the SCB to command a servo shutdown:

- The serial packet stream from the ACC (or the Palm Vx if it is in control) fails
- The integral of any tachometer fails to match the change in the low resolution encoder reading on the corresponding antenna axis
- The ADC overflows due to a large voltage from a tachometer for 5 consecutive samples
- A motor goes over temperature
- The watchdog timer expires (triggering a reset of the microcontroller).

In the event that a low resolution encoder fails, it can be difficult to move the telescope at all due to the logical interlock described in the second item above. Thus, an option was added to disable this comparison between the tachometer integral and the change in the encoder in order to deal with this rare situation.

3.4.2. ACC

The “servo” process on the ACC will command a servo shutdown if:

- The high resolution encoders fail to report a position
- The position reported by the high resolution encoders differs substantially from the low resolution encoders (reported by the SCB)
- The number of serial packet errors exceeds a specific threshold.

In addition, the “servo” process will refuse to enable the azimuth servo if the air pressure system does not show a fault at startup time (which it should prior to releasing the azimuth brake). This feature protects any person who may have manually released the brakes using the temporary brake

release button in the antenna cabin. This button engages an adjustable timer circuit that releases the azimuth brakes for (up to) ten minutes to allow personnel to rotate an antenna by manual force in case it is impossible to start the drive system. Finally, the ACC has the ability to command a reset of the SCB microcontroller via a digital output line on the VMEbus.

3.4.3. *Motor amplifiers*

The motor amplifiers have two electronic circuit breakers: high-speed and low-speed. Specifically, the amplifier will shut down immediately if the current exceeds 75 Amp, and after 15 seconds if the current remains above 50 Amp. The low-speed breaker protects the motor in the event of binding due to mechanical overload (such as a brake in the “released” state failing to fully release), or an electrical short causing overload of the output. These breakers have been triggered only very infrequently in operation because the SCB software limits the commands to the amplifier to safe values. In addition, an amplifier will fault and shutdown if: the motor goes over temperature, the amplifier board goes over temperature, or any significant failure in the supporting electronics occurs, including power supply voltages exceeding their specification range.

4. **Portable manual interface**

There are several reasons to include a manual, portable control interface for the antenna. In order to sample a broader range of spatial scales on the sky, interferometers like the SMA frequently need to have their antennas transported and redistributed across the available pads. To facilitate loading onto the transporter vehicle, the antenna must be driven to zenith and to a particular azimuth. It is convenient to have a simple hand interface for the transporter crew to locally operate the antenna (rather than entering cryptic commands on a keyboard somewhere). In the system described here, the antenna can be driven by the SCB via the Palm Vx interface completely independent of the operating state (or even the presence) of the ACC.

4.1. **Palm Vx computer**

The Palm Vx is a small, lightweight palm-sized computer package containing a 160×160 pixel greyscale liquid crystal display (LCD), a Motorola MC68328 microprocessor running at 20 MHz, and a traditional RS-232 serial interface (Figure 7a). Unlike other models manufactured by Palm, it draws its power from rechargeable, long-life lithium-ion batteries. The LCD screen continues to work even at low temperatures (near 0° Fahrenheit), and a backlight is available for use in the dark. Each Palm Vx has been embedded in a protective DelrinTM case that is comfortable to hold in one hand, and has a replaceable transparent window to protect the screen from the elements. There is a hardware E-stop button mounted onto the top of the case which is placed in series with

all other E-stop buttons on the antenna. The wires for this button, along with the serial data and power supply lines all run through a single cable with a circular connector. At the other end of the cable, the power supply lines are split out into a separate regulated power supply. With this power connection, the lithium-ion batteries will remain fully charged despite the continuous drain from the serial line circuitry.



Fig. 7.— (a) Photograph of the Palm Vx hand controller embedded in its black DelrinTM case. The circular connector at the top carries the power supply, serial communication lines, and the E-stop circuit wires. It can be connected either inside or outside the antenna cabin. (b) An example display on the Palm Vx hand controller showing the elevation axis under manual control. The +ELEV and –ELEV buttons will accelerate the antenna, while the MAINTAIN button will maintain the current velocities. If the user releases his finger from the touch screen, any active axis will decelerate to zero within a few seconds.

4.2. Manual control features

The SCB continuously transmits status values to the Palm Vx which serves as a convenient display terminal for personnel inside the antenna cabin. This condition is termed “remote mode”. The operating program on the Palm Vx is written in C and has many different pages that display the antenna position, velocity, motor currents and temperatures, as well as encoder zero values,

servo gains and filters, and tachometer calibration settings. More powerfully, the Palm Vx program can also be used to take manual control of the velocity servo loop away from the ACC into a “local mode”. If local mode is requested while the servo is active under remote control, it is first smoothly decelerated and disabled before control is passed.

Local mode always begins with the servo disabled. One or both axes of the antenna can then be activated via the touchscreen. The antenna can then be moved up and down in elevation and/or left and right in azimuth using a traditional cross layout of software buttons on the touchscreen (Figure 7b). These buttons increment or decrement the velocity, or stop the antenna. In effect, only one button can be depressed at a time. When neither button for an axis is depressed, the SCB automatically slowly decelerates toward zero velocity. If the button is depressed again, acceleration would resume from that point. If the velocity is non-zero, then the “maintain” button appears which, if depressed, will maintain the current velocity in both axes. The soft stop button in the center will automatically engage a rapid decaying velocity sequence down to zero velocity prior to engaging the brakes. While all of this is happening, the antenna position and velocities are displayed and updated on the touchscreen at about 1 Hz. There is also a slow speed mode called “turtle mode”, in which the velocity steps are reduced by a large factor and the velocity units displayed change from $^{\circ} \text{ s}^{-1}$ to $' \text{ s}^{-1}$. This mode is useful for fine positioning of the antenna under manual control, for example when installing the subreflector in the antenna barn. The clock time on the Palm Vx is updated periodically from the ACC clock time, which allows the Palm Vx to display the angle between the Sun and the telescope pointing direction, alerting the user with a flashing field when it becomes less than the avoidance criterion (see §3.3.4).

For safety purposes, the local mode never times out, however the servo will be automatically disabled if an idle timeout of a few minutes is reached. If the Palm Vx is ever disconnected or otherwise fails to communicate while in local mode, the SCB will immediately reassert control over the antenna, entering remote mode and shutting down the servo if active. If the antenna has been mistakenly left in local mode, control can be usurped remotely but only by entering the default password in the terminal control program (and only if the local user did not enter an optional temporary password when local control was taken). A third mode exists called “lockdown”, in which the user must enter a password. In this mode, control cannot be usurped and no other user can use the Palm Vx to move the antenna, which can offer additional protection from unaware co-workers in the event that an E-stop padlock system is unavailable, and one needs to climb on or under the antenna.

Further details on the operation of the Palm Vx can be found in Hunter (2000). The Palm Vx has been an intuitive and popular device among the daily telescope operations and maintenance crew (Christensen et al. 2008). The original devices continue to function well, perhaps longer than expected, and sufficient spares remain on hand.

4.3. Emergency stowing via telephone

The SMA operates unattended during the early morning hours of weekdays, controlled from a room in Cambridge or Taipei (Christensen et al. 2008). Because weather conditions can become severe quite quickly on Mauna Kea (Cherubini et al. 2009), to provide an additional level of safety, a fourth mode of servo operation called “telephone mode” was programmed. This mode was created to allow the operator to stow the antennas in the condition that internet connectivity is lost, but telephone connectivity remains. A commercial device accepts calls, and if the correct access code is entered, it presents a menu which allows the caller to trigger a digital input on the SCB in one or more antennas via a multimode fiber optic cable. After 30 seconds of continuous activation of the digital input, if the telescope is on an outdoor pad, the SCB switches to telephone mode. It closes the environmental cabin door and activates a state machine which will start the drives (if necessary) and then accelerate each axis to 1/4 of full speed. For each drive, it runs at that speed until near the stow position, when it decelerates to a stop and turns the drive off.

5. Performance

The “servo” program running on the ACC has the ability to collect and record an extensive set of real-time data to a disk file for testing purposes. This facility was used to record the performance of the servo in action.

5.1. Tracking

The typical two-dimensional rms tracking error of the antennas in calm conditions is $\sim 0.3''$ rms. An example of data acquired from antenna 2 on 2013 January 9, nearly ten years after the inauguration of the SMA, is shown in Figure 8. The windspeed was only 2.2 m s^{-1} . Over a 200 second period, the rms error in azimuth is $0.161''$ and in elevation is $0.266''$, with mean errors of $-0.10''$ and $+0.03''$, respectively. The mean total error angle (on the sky) is $0.25''$, and the fraction of time that this error exceeds the specification of $0.7''$ is only 1.2%, with a maximum excursion of $1.4''$. The tracking errors remain low for typical wind speeds of $< 10 \text{ m s}^{-1}$ but can reach 1-2'' for high wind speeds of $15\text{-}20 \text{ m s}^{-1}$. The antennas are stowed for safety by the operator when the wind speeds reach 30 m s^{-1} .

Some radio telescopes suffer problems at very low tracking rates, which occurs when the sign of the tracking direction changes. This will occur in elevation at meridian transit for all sources, and in azimuth at two specific points along the track of sources that transit between the zenith and the pole. The performance in these conditions has been tested on both axes, decelerating smoothly from $+0.15'' \text{ s}^{-1}$ to $-0.30'' \text{ s}^{-1}$ over a 10 minute period and the tracking performance is excellent: the rms is $0.11''$ in elevation and $0.15''$ in azimuth. At the lowest elevations ($\leq 15^\circ$), the elevation

tracking on some antennas currently degrades due to mechanical effects (stiction), likely caused by the combination of a small misalignment of the ballscrew axis with respect to the elevation axis and the elevation balance point being at much higher elevation.

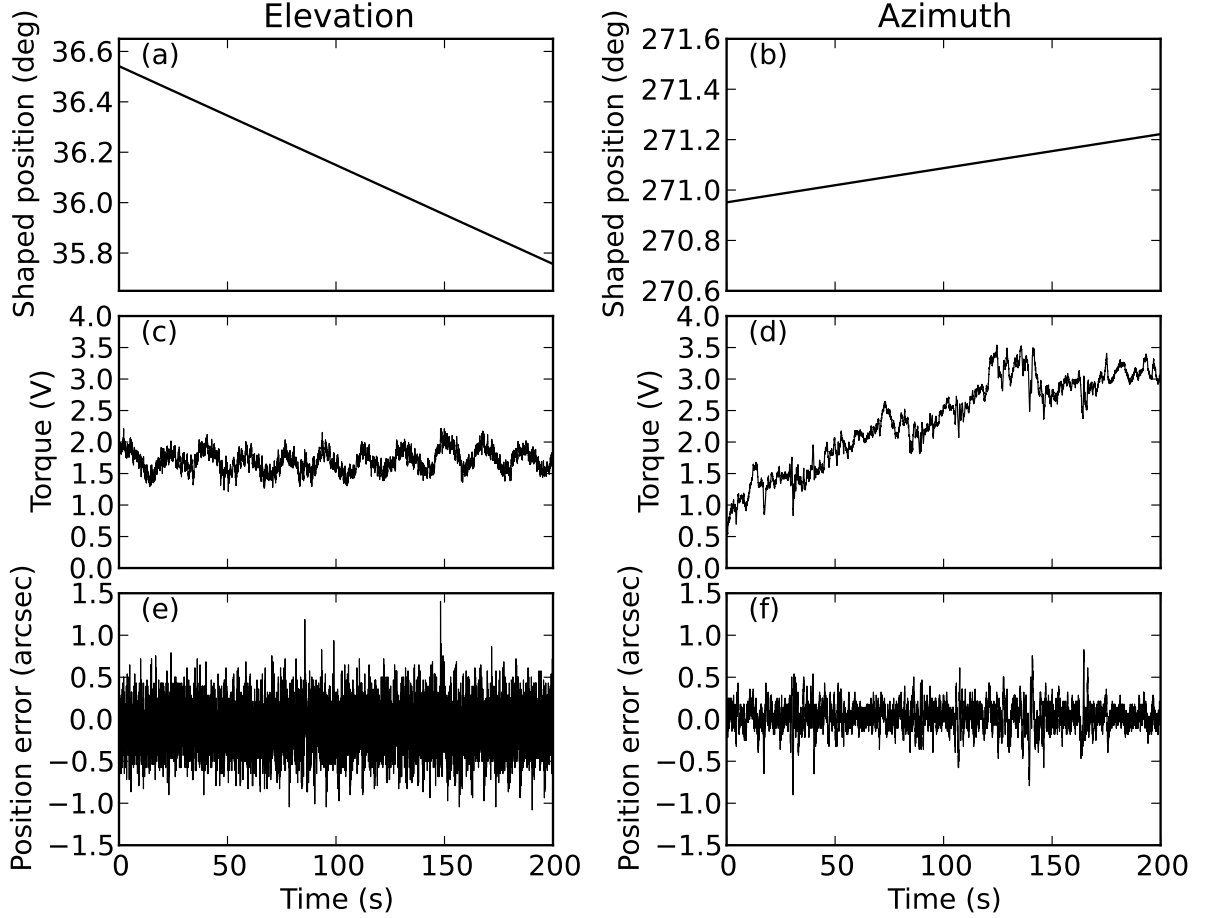


Fig. 8.— Servo performance while tracking a setting source. Panels (a) and (b): the commanded axis position in degrees. Panels (c) and (d): the torque command to the motor. Panels (e) and (f): the difference between the command position and the actual position reported by the high-resolution encoder (arcsec). The rms tracking error is $0.161''$ in azimuth and $0.266''$ in elevation.

5.2. Slew rate, acquisition time, and fast switching

Historical measurements of the time required for the antenna to slew to and acquire a new source are presented in Figure 9. For slews greater than $\sim 2^\circ$, the total time can be parametrized

independently for the two axes in the form of a constant plus the slew angle divided by the maximum slew velocity. The constants are 1.7 s in elevation and 3.1 s in azimuth.

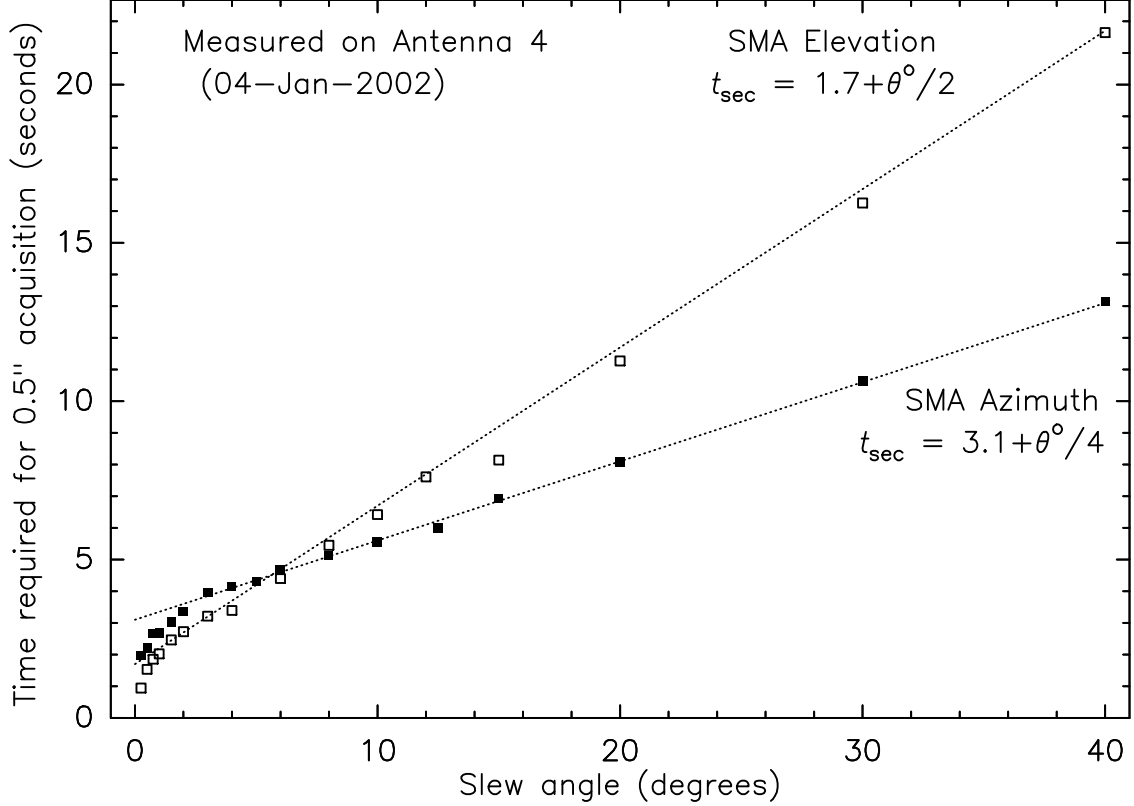


Fig. 9.— Measurements of the source acquisition time in seconds as a function of the slew angle in degrees along each axis. Filled points are for azimuth slews, and open points are for elevation slews. The lines are approximate fits to the large angle data points.

Although standard SMA observations do not typically use fast switching, the performance of the SMA servo has been recently measured when switching 5° in azimuth and 2.5° in elevation from the science target to the gain calibrator every 20 seconds. The SMA servo achieves a 70% duty cycle, where the duty cycle is defined as the time spent integrating on the target or the calibrator (with a total tracking error less than $0.7''$) versus the total time. Enforcing a tighter limit of $0.3''$, the duty cycle is still 65%. For these two cases, the mean total tracking errors during the intervals after a source has been acquired are $0.175''$ and $0.155''$, respectively.

5.3. Maintenance

The servo system requires very little maintenance. To demonstrate, the maintenance reports stored in the SMA engineering logs accessible from the SMA Observer Center (Katz et al. 2008; Petitpas et al. 2010) were reviewed. In over 10 years of deployment, only two chips have failed in service on an SCB. One was a digital output driver, and the other was one of the digital input optical couplers. Several working spare boards are available for quick installation when such repairs are necessary. In addition, in one antenna, both the charger for one of the Palm Vx units and the power supply driving the limit switch circuitry needed to be replaced in 2005. There are occasional problems with the connections of the 14 short fiber optic cables that connect the commercial parent and daughter boards on the motor amplifiers. In normal operations, unexpected shutdowns of the servo are very rare, and are usually an indicator of slowly deteriorating mechanical conditions, such as in the quality of the mesh of the azimuth motors to the bull gear or in the lubrication of the elevation ballscrew.

6. Summary

The digital servo control system for the SMA antennas was designed and developed in the SAO submillimeter receiver lab in 1998-1999 and commissioned on an SMA prototype antenna in late 1999 and early 2000. Many improvements to the software were added over the subsequent two years following the growing deployment of production antennas to Mauna Kea. The EPROM firmware of the SCB has remained unchanged since November 2002. The system has been reliable, provided the necessary flexibility for operations, and has been easy to maintain despite the sometimes harsh conditions of the mountaintop site. The system represents a successful example of a modern digital servo system which can serve equally well for the routine operations of a facility observatory like the SMA, or as a platform for the development and testing of advanced servo control algorithms.

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